Report of the GOES R+ EUV Sensor Workshop

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Introduction

Since 1974, the National Oceanic and Atmospheric Administration (NOAA) has operated a series of satellites at geosynchronous orbit to provide critical weather observations. This satellite system is known as the Geosynchronous Operations Environment Satellites (GOES). In addition to the global weather pictures, the GOES system also monitors space weather. A suite of instruments known as the Space Environment Monitor (SEM) system currently monitors solar X-rays, energetic particles, and the local magnetic field.

On the next series of GOES spacecraft, designated as GOES NO/PQ, an operational EUV sensor has been added to the SEM suite of instruments. The EUV sensor will monitor the solar EUV Irradiance between 5 and 125 nm in five broadband wavelength bands.

The spacecraft series beginning with GOES R is currently in the definition phase. A review of solar EUV requirements and objectives is part of this process. To facilitate the design objectives, a workshop on the EUV sensor requirements was held. This report is a compilation of the workshop presentations, discussions, and conclusions. It is not intended to be a transcript of the entire workshop.

The following Announcement was sent to prospective workshop attendees. Invitations were also sent to specific individuals to ask for presentations on topics important to review for the GOES R+ EUV program. From the responses, the agenda (listed after the announcement) was formulated. A complete list of workshop attendees is available in Appendix C.

ANNOUNCEMENT

GOES R+ EUV Sensor Workshop

28 - 29 October 2002
at NOAA/SEC Boulder, CO

Purpose of workshop
To clarify and refine the operational solar EUV measurement requirements for the GOES program and to examine various methods and techniques of meeting these requirements.

Background:
Solar EUV radiation is a primary source of energy and one of the main sources of variability for the thermosphere and ionosphere. Systems affected by the impact of variable EUV flux are satellites in low-earth-orbit due to changes in atmosphere density, and various forms of communication and navigation systems due to changes in the electron density. Typically, proxies such as F10.7 are used to specify the solar forcing of the upper atmosphere but this introduces errors into specifications and predictions of the environment. Measurements of the solar EUV flux are needed to reduce this source of error.

On the next series of GOES spacecraft (planned for launch in 2004), there will be an operational EUV sensor that will monitor the solar EUV flux between 5 and 125 nm in five broad wavelength bands. Because of challenges in achieving instrument specifications, it is valuable to explore alternative methods of measuring the solar EUV flux for the next series of GOES EUV sensors. It is likely that these alternate approaches might provide the reliability and sensitivities that are required. For instance, what are the emerging technologies that will provide better wavelength isolation and better visible light rejection?

Workshop Goals:
We are now setting the requirements for the EUV sensors for the next series of spacecraft, referred to as GOES R+, to be launched sometime after 2010. The specifications for EUV measurements on GOES R+ must satisfy the user community needs but must also be achievable within the resources that are available.

The GOES R+ EUV Sensor Workshop will address the issues described above. The workshop will be 1.5 days long and cover the following three topics in each of three half-day sessions.

1. Customer needs and requirements
2. Existing technologies that will meet these requirements
3. New and emerging concepts and technologies that may contribute to better monitoring of the solar EUV flux.

Some of the questions that should be raised (and may be answered) at this workshop are as follows.

1. What are the operational customer needs that flow down to EUV measurements?
2. What specific EUV measurements are needed to satisfy the customer needs?
3. What technology areas exist today for meeting these requirements?
4. What are the high risk areas where today's technologies will not meet the measurement requirements?
5. What is the likelihood that future technologies will meet these requirements?

GOES R+ EUV Workshop Agenda

Session 1: Solar EUV Requirements 8:30 - 1:30

Chair:Tim Fuller-Rowell

8:30	Introduction	Rodney Viereck and Tim Fuller-Rowell (NOAA/SEC)
9:00	Solar EUV Variability	Judith Lean (NRL)
9:45	Solar EUV heating of the Atmos.	Stan Solomon (NCAR)
10:10	Satellite Drag	Frank Marcos (AFRL)
10:45	Break	
11:00	Satellite Drag	Kent Tobiska (SET)
11:35	Ionospheric Effects on Systems	John Goodman (RPS)
12:10	Round Table Discussion	(working lunch)

Session 2: EUV Sensors of today 1:30 - 4:00

Chair:Frank Eparvier

1:30	SOHO SEM	Don McMullin (USC)

2:05	Solar Irradiance Sensors on SNOE,TIMED, and SORCE	Tom Woods (CU)
2:40	GOES EUV Sensor	Rodney Viereck (NOAA/SEC)
3:15	Round Table Discussion	

Session 3: New EUV Sensors and Technologies Monday 4:15– Tuesday 12:00

Chair:Greg Berthiaume

Monday

4:15	SDO EVE: Example of Future EUV Irradiance Sensors	Frank Eparvier (CU)

Tuesday

8:30	Developments in EUV Filters	Rich Capps (LUXEL)
9:10	Developments in EUV Detectors	Gregory Berthiaume (MIT)
9:45	Break	
10:00	Wide Bandgap Photodiodes	Shahid Aslam (Goddard)
10:35	Future EUV Sensor Designs	John Seely (NRL)
11:00	Fresnel Zone Plate Alternative to improve GOES EUVS performance	James C. Bremer (Swales)
11:30	Round Table Discussion	

Session 1: Solar EUV Requirements:

Session 1 was devoted to presentations and discussion of the future needs for customers that use the NOAA solar EUV measurements. The objective of Session 1 is to be able to ultimately define what specific EUV measurements will be needed.

Solar EUV variability:

It is clear that the solar EUV is quite variable, and on many time scales (Lean et al., 2002a). The variability of solar EUV can be seen on a scale of years, such as has been observed over the solar cycle, and days, as can be seen over the period of a solar rotation. Also, there have been observations of very rapid changes in solar EUV irradiance on the scale of minutes, such as in the case of solar flares and other eruptive events (Meire, et al. 2001; Ogawa et al., 1998). It has also been shown that different regions of the solar EUV spectrum behave differently on all time scales (Warren et al., 1998, 2001).

Customer needs:

The needs of solar EUV measurements is dependant on the needs of specific customers. Rarely, is there a customer that requires EUV measurements directly for operations. Rather, the users identified as customers for EUV measurements are interested in other specific parameters that are significantly influenced by the solar EUV and its variability. The exception to this, are customers looking for accurate solar data for the continued development of physical solar models. In operations, the EUV measurements customers most want are those that fit into operational models that they use to then specify the parameters they are most concerned with. For example, the Air Force is greatly concerned with the neutral particle density of the upper atmosphere, needed to monitor satellite drag. Global Positioning Satellite (GPS) users are concerned with phase delays in the navigation signals induced by changes in the electron content. Some HF communication customers are more concerned with variations in the ionosphere. These customers require knowledge of the solar EUV irradiance, however, they each request the EUV irradiance expressed to them as a direct model input or an index parameter that they will then use, in conjunction with other indices and inputs, to specify the environmental conditions that each is concerned with. Currently, solar variability, as an input to atmospheric and operations models, is expressed most widely as the F10.7 index value. A daily average value as well as a running mean of 81 days are typical inputs to account for solar variability. However, since the F10.7 is not derived from solar EUV measurements, there can be larger errors induced in systems that rely on the F10.7 as an indicator of solar EUV variability.

Most recently, an index identified as the E10.7 was created to address modeling errors that result from using the F10.7 for variability of factors driven by solar EUV irradiance. The E10.7 is derived from the SOLAR2000 empirical solar variability model (Tobiska, et al., 2000). Since the SOLAR2000 variability model is derived from actual measurements of the solar EUV, the E10.7 is an expression that is designed to more accurately represent the variability in solar EUV irradiance. In this way, the E10.7 is an index value that is readily available for customers, expressed in a format that existing models and operation procedures can readily interpret.

The implementation of the E10.7 index is a possible approach to consider for the GOES R+ epoch, however, the operational models are expected to advance beyond the single index requirement in order to produce the fidelity required to reach the geo-space specification goals for GOES R+.

In this example, the E10.7 index (or any index derived from a model) is only as good as the model that produces it, in this case SOLAR2000. It should be noted that the SOLAR2000 model is just one model currently used in operations, and that SOLAR2000 does not always agree with observations or other models, and these comparisons can differ by a factor in absolute value and variability (Lean, et al., 2002b).

Forecasting:

All presentations of customer needs included a need to forecast the solar EUV irradiance. In terms of operations, this need would translate into a need to predict, or forecast, the model input parameter, or the measurements such a parameter is based on. This requirement further demonstrates the increasing role of modeling in the specification of the geospace environment, whether the specification is immediate (as in a nowcast) or for a time period in the future (forecast). In terms of satellite drag requirements, forecasting improves space situational awareness, which translates into improved ability to accurately locate, track and target space based assets. Forecasting also reduces risk in HF communications by allowing operators to modify path geometry and other system parameters in advance of predicted solar-terrestrial conditions. In operations, forecasting is expected to be required for time scales from 3 hours to 72 hours.

Solar EUV measurement requirements:

From the presentations and discussions following session 1 in the EUV the workshop, there was no clear consensus among the attendees as to what specific wavelengths or wavelength ranges should be measured during the GOES R+ time frame. What did become clear, and was in general agreement, was that there is an important need for the GOES R+ spacecraft to monitor the solar EUV irradiance *as needed to improve the abilities of operational models to nowcast and forecast the geospace environment.*

The estimates of goals for the GOES R series is to provide measurements with the required accuracy and precision to specify the neutral atmosphere density to better than 5%, and specify the electron density to 1 total electron count (TEC) unit. However, it should be noted that during the workshop, the EUV requirements for models to specify these parameters were unknown. Without knowledge of model input requirements and sensitivities and accuracies, it cannot be determined what specific EUV measurements will be required. This is an area of recommended study for future definition workshops.

Session 1: Conclusions

For discussion of Session 1 objectives, the wavelength range of the solar EUV under consideration for the GOES R+ measurements was specifically limited to wavelengths below Ly-alpha (121.6 nm). This region of the solar spectrum contains a few bright emission lines and a few regions of continuum. Within this collection of lines and regions, there are differing scales of temporal variability, and differing effects on the geo-space environment.

To be able to meet the expected operational customer requirements for the GOES R+ epoch, monitoring of this region will be required on a continuous basis such that the current state of the geo-space environment can be specified (nowcast) through direct measurement or model, and that the expected future state of the geo-space environment can be reasonably predicted (forecast) through models.

At the time of this workshop, it is not clear that it is necessary to monitor the entire solar EUV region below 121.6 nm to accomplish these objectives.

By example, the SOLAR2000 solar EUV model has empirically captured direct solar EUV measurements from various instruments, observing a combination of low resolution bands and high-resolution spectra, and specifies the state of solar EUV flux as a nowcast and forecast, expressed as the index E10.7. However, it is expected that as currently defined, the E10.7 will be too limited for the GOES R epoch.

Through the expected advancement of understanding and model capability, nowcast and forecast requirements can be met with solar EUV measurements of a few bright emissions or bands, to be determined at a later date.

Session 2: EUV Sensors of today

Session 2 focused on the current state of solar EUV sensors that may be able to provide the measurements for operations presented in session 1. The instruments presented included broad band instruments as well as spectrometers. The instrument concept and capabilities were presented. A summary of each instrument presentation can be found in Appendix A. A complete copy of each presentation is included in Appendix B. Rather than repeat a specific discussion of each instrument, the section below will focus on describing the type of instrument and the current state of the technology that can be adapted to a GOES instrument for operations.

Solar EUV Photometers (low resolution):

Solar EUV filter photometers are probably the simplest and smallest instrument type used to monitor the solar EUV. Filtered photometers also have the poorest wavelength resolution. The most common detector flown today are highly stable, absolute silicon photodiodes. These devices have a long and successful history of flight programs from sounding rockets to satellites. Solar EUV photometers measure the integral EUV flux in a relatively broad bandpass. Many times, as is the case for SONE/SXP and SOURCE/XPS measurements, the bandpass is limited by an EUV filter placed in front of, or directly on the silicon detector (Bailey et al., 1996; Woods, et al. 2000). Advantages that photometer based instruments have is that they can provide absolute solar EUV measurements, at high time cadence, and require smaller amounts of spacecraft resources. The main disadvantage to this approach is that the selection of wavelength sensitivity is limited to filter technology available. Additionally, filtered photometers are susceptible to contamination on the forward filter.

Transmission grating photometers (medium resolution):

A modification of the filtered photometer approach is the addition of a transmission grating. This type of instrument provides improved wavelength resolution over filtered photometers. Solar radiation first passes through a transmission grating that disperses the EUV radiation. The highly stable Si photodiodes are positioned in the dispersed radiation. This way, the bandpass is selectable by placement of the detectors with respect to the central image of the grating. This technique allows for better definition of exact bandpasses to monitor, and is less susceptible to large increases in soft X-ray. The maximum resolution that can be achieved (the smallest bandpass) with this technique is nominally 1.7 nm. This technique is currently in use on the SOHO/SEM instrument (Hovestadt et al, 1995) and is currently the planned configuration for the GOES N EUVS instrument and the upcoming SDO/EVE instrument (Eparvier and Woods, 2002). The disadvantages of this instrument is that scattered visible light can be a problem, and therefore, filters are still required for visible light rejection. This has been identified as a problem when trying to monitor solar EUV flux in the 50 – 100 nm region, where flux levels are low and the combination of grating transmission and available filter materials is poor (Viereck 2002).

Solar EUV Spectrometers (high resolution):

EUV spectrometers provide the highest spectral resolution of the instruments presented, at a reasonable time cadence. The EUV Grating Spectrometer (EGS) on the TIMED spacecraft (Woods et al., 1998) has a resolution of 0.4 nm and covers the EUV spectrum from 26-195 nm. EGS has a 10 second integration time, however, due to its orbit, observations are limited to 3 minutes per orbit (approximately 96 minutes). EUV spectrometers today use position sensitive detector systems. These detectors are usually microchannel plate (MCP) based or charge coupled device (CCD) systems. Throughout the flight history of EUV spectrometers, they have been difficult to calibrate and have demonstrated a relatively high sensitivity to contaminants and other factors affecting stability over time. Additionally, these systems require much more in the way of spacecraft resources in terms of mass, power, and data rates. They also add complexity to implementation and operation procedures. However, they are the only way to obtain high resolution spectral irradiance measurements. The TIMED/EGS instrument has a stated calibration accuracy <10% and measurement precision <2% (Woods, 2002). The TIMED/EGS instrument is also supported by a rocket underflight calibration program which will be able to validate (or correct as needed) the absolute accuracy and stability of the TIMED results.

Session 2: Conclusions

Without a clear definition of what EUV measurements will be needed, it is difficult to recommend specific instruments or instrument concepts. However, in looking at the types of instruments and technology currently available, a few boundary conditions can be identified.

Lines or bands:
A recurring point in discussions of instruments and measurements can be broken into a discussion of lines or bands. That is, ***if*** the EUV measurement requirements do not specify a need to measure individual lines in the solar spectrum, but rather the integrated energy with a specific band of the spectrum, a transmission grating based photometer instrument would be able to provide the needed measurements without a large need of spacecraft resources.

However, this method would be limited to a resolution of 1.7 nm, and as such, if there is a requirement for monitoring individual lines, or bandpasses significantly less than 1.7 nm, than a more conventional grating spectrometer will be required. Depending on the specifications for high resolution measurements, a position sensitive detector system may be required.

Accuracies and Precision:
Current EUV instruments and technology have demonstrated absolute accuracy in EUV measurements to the 10% (1s) level (McMullin, et al., 2002; Woods, 2002). Long term stability is on the order of a few percent per year. Any instrument consideration for the GOES R+ time frame should meet these values at a minimum. Such a requirement will also place a requirement for extensive pre-flight calibration and traceability as well as in-flight monitoring. It should not be a surprise that GOES R+ solar irradiance measurements will be compared against concurrent operating instruments as well as past measurements through models and proxy measurements.

Time Cadence:
EUV measurements must be made on a frequency greater that the final data product need. The instruments in current use have provided EUV measurements with nominal integration times of less than 1 minute.

Session 3: New EUV Sensors and Technologies

The GOES R series of spacecraft are expected to provide solar EUV irradiance measurements starting in the year 2012. Session 3 was dedicated to presentations and discussion on the topics of new EUV sensors and developments that may be available in the near future for consideration for the GOES R+ EUV sensors. Presentations were delivered for new complete EUV instruments as well as developments in EUV components and alternative measurement concepts. A summary of each presentation for session 3 can be found in appendix A. The complete presentations are available for review in Appendix B.

EUV Variability Experiment (EVE):

The EUV Variability Experiment (EVE) is currently in development for NASA's Solar Dynamics Observatory (SDO). EVE is being designed to study the solar EUV irradiance from 1-120 nm, at 0.1 nm resolution with high absolute accuracy (<7%) and long-term precision (1-4%). The EVE approach to meet these goals is to use a combination of instruments. The solar EUV spectrum is measured over much of the wavelength range by two radically different methods: an optical grating spectrometer with CCD detector (Multiple EUV Grating Spectrometer, MEGS), and an optics free, rare gas photoionization chamber (Optics Free Spectrometer, OFS). The multi-channel MEGS provides the dispersion needed to achieve the required spectral resolution. But optical elements are notorious for degradation when exposed so solar radiation, and for spectral contamination by overlapping orders. The OFS measures the solar EUV energy, by counting the electrons produced by EUV ionization of rare gases, with the absence of optical elements and overlapping orders. Five broad spectral regions are further monitored with a transmission grating photometer (EUV Spectrophotometer, ESP). This multi-instrumented approach is designed to provide inter-comparison and inter-calibrations to the EVE measurements to ultimately produce a data set of the highest quality in terms of accuracy and long term precision. The EVE program is expected to provide simultaneous measurements with GOES R+ instruments.

Advances in thin-film filters for the EUV

New advances in EUV filter fabrication techniques may be able to provide alternative filter material combinations that today are considered unstable, or too fragile. Promising advances may soon provide a 15% increase in signal and a 32% increase in measurement efficiency over what is currently available today as standard filters. Also, promising filter material combinations for better visible light rejection and bandpass selection may become available with the ability to separate incompatible materials with stable, EUV transmissive polymer membranes.

Advances in CCD technology

Single-element silicon photodiodes have been demonstrated to be highly stable in the EUV. Recent advances in multi-element silicon array detectors (CCDs) should be able to provide equivalent stability, thus, improving the long term stability of CCD detector systems. Additionally, continued developments in non-planar arrays can make CCDs available for use in EUV applications that require curved focal planes to achieve even higher resolution than possible with a flat detector system.

Solar-blind Detectors and methods

Developments in EUV detectors that are blind to visible light (so called "solar-blind" detectors) can offer future advantages where current instruments are limited by poor visible light rejection. Wide bandgap detectors are currently being developed that could have the necessary sensitivity in the EUV and also the required limited sensitivity to visible or out-of-band UV radiation. These developments are still in the early stages and as such, it is difficult to estimate the availability for a GOES R mission.

Other solar-blind alternatives may be closer at hand. A proposed solution to the GOES N C and D channel poor performance problem is the use of a solar-blind sensor using a photocathode and Si photodiode. This would avoid the need for an exotic EUV filter to provide visible light blocking. Estimates using this technique indicate that the original specification for the GOES N EUVS channels C and D would be met by such a device. The level of development is not great at this time and may only require proof of concept testing.

Fresnel Zone Plates for EUV

Another alternative approach to meet the C and D channel specifications is the use of a centrally-obscured Fresnel Zone Plate (FZP) (Bremer 2002). This approach is most closely related to a transmission grating photometer, where the transmission grating has been replaced with a Fresnel Zone Plate. The basic function of an FZP is similar to the transmission grating. The difference being that with a transmission grating, the spectrum is dispersed linearly, and with the FZP, the spectrum is dispersed concentrically. In the GOES R application, this would focus a narrow band of radiation at a given distance from the FZP. Other wavelengths would be defocused in the same plane. The de-focused radiation would contribute a much smaller amount to the detector response because the flux per unit area would be greatly reduced. Calculated estimates of signal to noise indicate a great improvement over the transmission grating approach for EUVS channels. The disadvantages for this technique are that each FZP may be limited to only one channel, and each FZP would have to be much larger than the currently used transmission grating, thus increasing the size and weight of the instrumentation required. Additionally, the fabrication of such FZPs would have to first be addressed and is not considered to be a trivial task, but also not considered to be beyond current capabilities.

Session 3: Conclusions

NASA Sun-Earth Connection missions, such as SOHO and TIMED, are continuing to provide fundamental research into solar variability and the effects on the geo-space environment. SEC missions planned for the future, such as SDO, should carry this effort into the GOES R+ epoch, and provide valuable support for the advancement of measurement and modeling techniques that can be adopted for operations. Instruments such as SDO/EVE and SHARPP will provide the next generation series of solar EUV instrumentation for GOES to consider for future missions.

Expected advances in EUV instrument components, such as thin-film filters and CCDs, can improve EUV instrument performance using mature designs. Continued development efforts, funded by NOAA, into new EUV devices, such as solar-blind detectors (wide band-gap devices), can overcome some of the limitations of current instrument designs. However, it is not clear that these new devices will be mature enough to consider as candidates for GOES R instruments.

Recommendations:

The GOES R EUV Workshop attendees presented and discussed many aspects of the current state-of-technology and understanding for solar EUV measurements, modeling, and effects on the geo-space environment. From this workshop, it became clear that there are a few areas that require specific study to better determine the requirements for GOES EUV measurements to meet operational objectives. The recommendations identified in this report will go a long way to providing the additional information needed to clearly define the next generation requirements for GOES EUV monitoring.

Operational customers presented the need for an accurate expression of the current and near future geospace environment driven by changes in the solar EUV irradiance. The operational requirement for EUV measurements, flow out of the input requirements for the operational models that determine the current and future state of the geospace environment (nowcasts and forecasts).

Operational customers have identified a goal for operations models to be able to specify the neutral atmosphere density to better than 5%, and to specify the electron density to 1 total electron count (TEC) unit. However, there was not a clear identification of what specific EUV measurements are required for input into operational models to derive these values.

> Recommendation 1:
> It is recommended that a study be completed to identify the potential models for the GOES R+ epoch that require solar EUV parameters for input, the format of EUV irradiance, and the sensitivity of the model results to uncertainty in the EUV irradiance specification.

It is the expected application of GOES R EUVS measurements that will determine the measurement resolution, accuracy, and precision requirements. After a review of future applications and adjustment for future maturity targets the measurements of the GOES R+ should be re-stated for subsequent reviews or workshops.

It is anticipated that even if it is ultimately determined that the models expected to be in use in 2012 at still too undefined to provide specifics, that the process will help identify the level of specification needed. This may help resolve, or at least better define the options available for measurement approaches.

> Recommendation 2:
> During the workshop, it was proposed that specific regions or bands of the EUV spectrum could be identified where either the solar emissions or the atmospheric cross sections were relatively featureless. By carefully selecting wavelength bins or regions, the solar EUV spectrum can be broken up into a few relatively large

> bands, that would require independent monitoring, and would be able to provide direct measurements of the solar EUV that drive the variability of the upper atmosphere (Solomon and Qian, 2002).
>
> It is recommended that a study be completed to identify specific regions of the solar EUV spectrum that could be monitored by this approach. This approach has been identified as being attractive to the GOES objectives as it may identify a strategy that can be implemented simply and effectively into NOAA operations, and build on current NOAA heritage and investments.

The question of exactly what lines or bands in the solar EUV spectrum to be measured by GOES remains open. This specific question could not be answered by the attendees of the solar EUV workshop, and as such, no consensus could be reached on the topic.

However, there exists anticipation that the operational solar models in use in 2012 will be significantly improved over those currently used today. The overriding assumption in this case is that within 10 years, with the necessary inputs, solar models will be able to specify the absolute solar EUV irradiance to within 5 percent. The advancement of solar models over the next 10 years is expected to benefit by continuing research programs currently underway in NASA's SOHO and TIMED missions. The development of solar model capability is expected to be greatly enhanced by NASA's Solar Dynamics Observatory (SDO), scheduled to launch in 2007. Model development and forecast capability are specific objectives for the EVE and SHARPP instrument suites on the SDO mission. With the resources and concentration in basic research now underway in solar EUV irradiance, it is reasonable to expect significant advances in future model capabilities for both nowcast and forecast GOES requirements.

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Appendix A

The following are summaries of the individual presentations during the GOES R+ EUV sensor workshop. A complete copy of each presentation is available in the workshop report supplement.

Session 1: Solar EUV Requirements

J. L. Lean, J. T. Mariska, H. P. Warren
Naval Research Laboratory, Washington DC.

Solar EUV Irradiance Variability

The current EUV experimental data base has insufficient spectral and temporal coverage to allow researchers to accurately specify (through models) the solar EUV spectral irradiance at any given time. This is partly because drivers of EUV variability (magnetic sources) occur in different regions of the solar atmosphere that have a wide range of emission temperatures and spatial scales. The solar EUV spectrum is a complex mix of emissions arising from the Sun's chromosphere, transition region and corona, with the emission line temperatures varying over two orders of magnitude (T= 10^4 - 10^6 K) and source region spatial scales extending from relatively compact chromsopheric plages and network to extended, global scale coronal loops. Specifying the solar EUV energy that is available for heating the Earth's upper atmosphere is further complicated by the differential absorption of upper atmosphere gases that modify the particular mix of chromospheric and coronal emissions that reaches any given altitude. It is therefore important to accurately specify the solar EUV spectral irradiance distribution at the top of the Earth's atmosphere, and its variability, as well as to understand and predict its effect on Earth's upper atmospheric environment. Because of the lack of a comprehensive observational database, solar EUV models, such as HFG, EUVAC, SOLAR2000, and NRLEUV are used to specify solar EUV irradiance specification on any given day. However, the models' estimates can differ by as much as a factor in EUV energy and variability. In anticipation of developing improved solar models, future EUV irradiance measurements must have high absolute accuracy and long term precision. Additionally, the rapid changes in EUV radiation due to solar flares must be monitored so that the models can be extended to include these shorter term variations Improving models such as NRLEUV, that are developed from the fractional contributions of the quite sun, active regions and coronal holes will also require solar imaging.

Stan Solomon and Liying Qian
High Altitude Observatory, National Center for Atmospheric Research

Solar EUV Energy Deposition in the Atmosphere

When considering the deposition of solar EUV energy in the upper atmosphere, GCM and photochemical models require daily average and relatively low resolution binning of the EUV irradiance. In looking at the effect of solar EUV energy on the upper atmosphere, it is clearly the driver for the higher atmospheric regions that affect satellite drag. This is especially true during solar maximum conditions. In a comparison of the solar vacuum-ultraviolet spectral variability, and its deposition into the upper atmosphere, it is clear that the soft X-ray and EUV portions of the spectrum have a much more considerable affect than the FUV portion of the spectrum. A series of studies was completed to look at the sensitivity of EUV model inputs for use in GCM's. Looking at the requirements for EUV input parameters into the models, higher and low-resolution wavelength bins were considered for modeling. Comparisons were made for solar minimum and solar maximum conditions. The study concluded that the low resolution bins, such as can be derived from broad-band measurements, were satisfactory in specifying the solar EUV irradiance. When looking at the energy distribution (as a function of wavelength) combined with the cross-sections of upper atmospheric constituents, there are certain efficiencies that can be exploited when either the cross-sectional value is relatively featureless, or the spectral distribution contains no strong, significant line emissions. By carefully selecting wavelength bins or regions, the solar EUV spectrum can be broken up into relatively large bands that require independent monitoring. There are a few problem areas with this approach, however, there are simple accommodations that can be made to provide these measurements as well, and alternatives can be further studied.

Frank A. Marcos
Space Vehicles Directorate, Air Force Research Laboratory

Dr. Joseph Liu
Air Force Space Command, Space Analysis Center

AIR FORCE SATELLITE DRAG REQUIREMENTS

The neutral particle density is directly proportional to satellite drag. At 400km, the increase in neutral particle density can vary 10 % due to day-today changes in the EUV flux. Over the period of a solar cycle, the neutral particle density can vary by a factor of 10. Accurate knowledge of the neutral particle density, and thus, accurate knowledge of the solar EUV flux, is a requirement for the Air Force to carry out many of its missions, and ultimately, Space Situational Awareness. Atmospheric neutral density and space environment forecasting research is the key for future precision Space Situational Awareness. Air Force current capability in drag error is 15% with a future goal of 5% for the 90 – 600 km region. In order to accurately predict satellite positions, forecasting of solar EUV inputs is necessary. For future requirements, there is a significant need to continue development of operational data driven physical and empirical models, of which, the solar EUV is a fundamental input.

W. Kent Tobiska, Bruce Bowman, Mark Storz, Steve Casali
Improvements in Operational Satellite Drag Estimation

The ability to specify, or characterize the upper atmospheric variability is critically important. Operationally, nowcasting is specifying the current state of upper atmospheric conditions. This is a key factor in space situational awareness. There is a current need to improve 72-hour forecasts of solar EUV irradiances, in order to forecast operational indices used to characterize the space environment. Currently, solar EUV irradiance flows into operational models through E10.7 index as nowcast and forecast input. Improvements in the near future (GOES N+ series) do not require changes to operational inputs or procedures. Improved measurements of EUV irradiance will flow into operations via E10.7. Near future advances in solar physics can be incorporated into E10.7 over the next decade. As such, improvements in EUV irradiance forecasts will also be reflected in improvements in E10.7 forecasts. Operational model inputs during the GOES R+ epoch will be able to realize additional benefits to improvements in E10.7 nowcasts and forecasts that will not require significant changes to operational inputs or procedures.

John M. Goodman
Radio Propagation Services, Inc.

IONOSPHERIC EFFECTS ON SYSTEMS

The influence of the ionosphere on radio systems falls into two general categories. Category 1 involves those systems which depend upon the ionosphere (i.e., involve the ionosphere as part of the system). Category 2 involves those systems for which the ionosphere is simply a nuisance. Some examples of of Category 1 systems include: VLF-LF Communication and Navigation, MF Communication, HF Communication, HF Broadcasting ("shortwave" listening), OTH Radar Surveillance, and HFDF and HF SIGINT. Examples of Category 2 systems include: Satellite Communication, Satellite Navigation (e.g., GPS & GLONASS), Space-based Radar & Imaging, Terrestrial Radar Surveillance & Tracking, and any other system for which the ionosphere is not necessary for conveyance. As such, variations in ionospheric conditions can produce variations in system performance. For users of these systems, proper use of planning tools such as ICEPAC, and VOACAP, help maintain system performance. Mitigation of disturbances is one solution available to users. Development of a number of prediction systems for use in system performance estimation and planning (e.g., the ITS suite of codes: IONCAP, VOACAP, ICEPAC) is required. Generally, it is the ionospheric variability which provides the biggest challenge to system users (vis-à-vis unpredictable SNR and signal distortion effects). To meet these challenges, a good space weather prediction methodology is needed. Development of new and/or improved physical relationships between Space-Weather parameters (e.g., IMF characteristics) and the global distribution of Ne in the ionosphere and plasmasphere. Development of sensors and/or techniques for the timely delivery of Space-Weather parameters.

Session 2: EUV Sensors of today

Donald R. McMullin and Darrell L. Judge
USC Space Sciences Center

Absolute solar EUV irradiance from SOHO CELIAS/SEM

The SOHO CELIAS/SEM instrument is a small, light weight, transmission grating spectrometer that monitors the solar EUV in two bands. The SOHO SEM has been in operation since December 1995 and has provided near continuous measurements of the solar EUV from 26 – 34 nm and from 01. – 50 nm. SEM irradiance measurements have a maximum cadence of 15 seconds, and show persistent 27 day modulation of the EUV flux as well as strong variations associated with known solar flares, CME's and other rapid solar events. The absolute accuracy and precision of the SOHO/SEM measurements have been monitored through a sounding rocket calibration program, in which an identical SEM instrument is periodically flown for comparison with the SOHO instrument. The rocket SEM is well calibrated pre- and post flight to verify its accuracy and precision over time. The SOHO/SEM data set has been shown to be accurate to 10% with relative precision 5% since 1995.

Overview of Recent Solar EUV Instruments Overview of Recent Solar EUV Instruments from LASP / University of Colorado

Tom Woods
LASP, University of Colorado

Since the 1970's, the University of Colorado/LASP, has been involved in solar irradiance measurements. These measurements have been primarily in the FUV and MUV regions of the solar spectrum. During the past decade, LASP programs have expanded into the EUV and visible ranges. LASP experience with instruments is mostly with grating based spectrometers and some filtered photodiode systems (photometers). Using thin film coated photodiodes, the instruments such as the SORCE XPS can provide solar irradiance measurements in various bands, depending on the type of coatings applied. The TIMED SEE instrument contains an XUV photometer system (XPS) and an EUV grating spectrometer (EGS). SEE is currently operating on TIMED and data products are generated daily, and available through the LASP web site. Based on the past experience of many LASP missions in the solar EUV, the author offers recommendations for the GOES EUV sensor package. The author has identified spectral measurements as providing the most useful information. When possible, multiple measurements using multiple techniques can provide important validation and redundancy. Expensive pre-flight calibration is a must, and when possible, in-flight calibration references should be included. A complete and more detailed summary of the author's recommendations is available in the complete presentation included in Appendix B.

Rodney Viereck
NOAA Space Environment Center

GOES EUV Sensor Overview

For the first time, a solar EUV sensor has been included in the Space Environment Monitor (SEM) suite of space weather instruments on the GOES N+ series of spacecraft. This new sensor design is based on the SOHO Solar EUV Monitor (SEM) instrument, in operation since December 1995. For the GOES mission, the EUV sensor has 5 channels (bands) that are meant to cover a much wider portion of the solar EUV spectrum than the SOHO/SEM instrument. The GOES EUV sensor is designed to measure flux levels from 1/10 solar min to 10 times solar max at a 30 second cadence. The absolute accuracy is estimated at +/- 10%. The 5 bands channels were designed to provide an integral measurement of the EUV energy in selected bands that have the greatest effect in upper atmosphere variability. Through the development process, it became apparent that technical difficulties would prevent 2 of the proposed channels from realizing the expected performance. This is due to the relatively low levels of EUV flux in the region of interest, the low performance of the thin metal filters selected, and the lack of alternative filters and detector systems available. Poor visible light blockage and low EUV transmission are the main challenges in resolving these issues. Multi-layered metal films originally specified were found to not be metallurgically stable over the time period required. Alternative approaches to improve the EUV to visible light signal ratio are still being sought. For now, the problem areas have been re-specified to work within the range of acceptable materials available, but may not meet the original intention.

Session 3: New EUV Sensors and Technologies

SDO EVE: An Example of Future Solar EUV Spectral Irradiance Monitors

Frank Eparvier and Tom Woods
University of Colorado, LASP

The Solar Dynamics Observatory (SDO) is the first mission in NASA's new Living With a Star program. SDO is a research mission with the goal to understand and learn how to predict solar variations that affect life on Earth. The EUV Variability Experiment (EVE) is designed to provide absolute solar EUV irradiance measurements and is one of three instrument suites selected. The SDO mission is scheduled to launch August 2007, in a geosynchronous orbit. An instrument suite to measure the solar EUV irradiance from GEO is an excellent candidate precursor for the GOES R+ EUV instrument. The core to the EVE approach is to make simultaneous measurements with different instrument types. The EVE instrument contains low resolution EUV photometers (ESP = EUV Spectrophotometer), higher resolution spectrometers (MEGS = Multiple-EUV Grating Spectrometer), and highly stable ionization spectrometers (OFS = Optics Free Spectrometer). The ESP and MEGS instruments operate at a high time cadence (1 – 10 s) whereas the OFS is used for in-flight calibration and stability and operates once daily or weekly as needed. The combined measurement approach is designed to give EVE the capability to measure the EUV spectral irradiance from 0.1 – 105 nm at a resolution of 0.05 to 0.1 nm. The time cadence will be from 1 to 10 seconds with an absolute accuracy of 7% or better and long-term stability targeted for 4 % or better. The EVE program also includes a significant effort for solar EUV model development and prediction capability. Additional details on the EVE instrument capabilities are included in the complete presentation in Appendix B.

Developments in EUV Filter Technology

Rich Capps
Luxel Corporation

Luxel filters (thin-film) have a long and successful heritage in space flight applications. Used as aperture windows, thin-film filters have been able to provide solar heat rejection, UV and visible light rejection, and contamination protection. Thin-film filters can also provide analytical spectral differentiation and isolation of spectral features determined by the transmission bandpass of the filter materials selected. Future improvements that Luxel is currently developing include a reduction in the wire mesh diameter. Throughput can be dramatically increased by the reduction in wire diameter. Luxel estimates that a 15% increase in signal and a 32% increase in measurement efficiency can be achieved. Luxel is also working on a polymer membrane support that can increase filter combinations available for the EUV by encapsulating active metals. It can also be used to separate incompatible materials. Strength improvements are also realized with the polymer membrane. A new deposition system and clean room facility will soon be operational at Luxel (Fall 2002). The new system will increase yield, provide improved thickness control, substrate temperature control, and will have a future load-lock capability. The new system will also make larger substrates available (8-inch and 12-inch capability) and multilayer capability. Luxel is also looking forward at investigating the possibilities that may be realized through EUV interference filters. The basis for this work is that interference effects are used to create normal incidence mirrors in the EUV, and perhaps such an application of interference effects could make new opportunities for EUV transmission as well. For the near future and beyond, thin-film filters are expected to develop in terms of higher throughput, larger sizes, durability improvements, and new passband and blocking options.

Developments in Si EUV Detectors

Gregory D. Berthiaume
MIT Lincoln Laboratory

Silicon photodetectors have been around for more than 25 years. Most major X-ray observatories carry Silicon CCDs. Recently, advances in Si processing have led to stable devices suitable in the EUV. Standard Si photodiodes have become available from NIST with demonstrated long term stability. However, for use as solar EUV detectors, there are some challenges. Silicon is an excellent visible light detector, and the solar flux is ~1E6 times greater in the visible than in the EUV. For this reason, Si detectors require visible light blocking filters or other optic schemes to avoid swamping the EUV signal. Depending on the EUV wavelength of interest, there is a limited choice of filters available, and for some regions, these filters have proven to be very fragile, sensitive to oxidation and sometimes unstable over time. Wide bandgap semiconductors avoid this problem because they are insensitive to visible photons. Silicon array detectors (CCDs) offer similar performance and stability characteristics as single element Si photodiodes, and offer additional advantages. Array detectors can provide imaging in the EUV as well as single photon counting. Disadvantages include an increase in susceptibility to radiation damage and increased operational and implementation complexity. Current and future development in CCD technology offer a minimized radiation susceptibility and non-planar detectors (curved focal surfaces) to possibly improve performance in Rowland circle architectures. For future applications, CCD technology is making progress in improved QE, stability, and radiation tolerance. Additional advances in non-planar arrays and solar blind (wide bandgap) arrays may increase the availability of CCD detectors to EUV applications.

III-V Compound Semiconductors for UV detectors
Shahid Aslam
GSFC, NASA/Raytheon ITSS

The Detector Systems Branch at GSFC (code 533) has begun a development program to produce solar-blind semiconductors for UV/EUV detectors. This type of detector is also known as wide bandgap detectors. Recent strides in the manufacturing of wide bandgap detectors have brought them to the “edge of possibility” for operations. To date, these detectors have been highly experimental, however, recently, NOAA has funded development efforts aimed directly at benefiting the GOES program objectives. To date, high quality u-GaN growth has been shown in the laboratory and both n-type and p-type doping in the GaN has been achieved. It is recommended that the development work continue. Upcoming objectives to further the advancement include fabrication of large area (1cm x 1cm) Schottky and pin photodiodes and advance simulations for QE estimates and understanding.

Solar-Blind GOES EUVS Sensors
John Seely
Space Science Division, Naval Research Laboratory

The GOES N EUV sensor design is not meeting the original specifications for channels C and D. These channels were intended to monitor the solar EUV flux in the 40 to 100 nm region. The filter materials baselined for the channels proved to be problematic and have poor performance characteristics in terms of visible light blocking. A possible solution to the channel C and D problem is the use of a solar blind sensor using a photocathode. The incident photon ejects a photoelectron from the photocathode that is accelerated to the diode. The diode current produced by the accelerated electron is much larger than would be produced by direct detection of the EUV photon. The advantages to this approach are high sensitivity to EUV photons, the photocathode is blind to visible light and has lower sensitivity to shorter wavelengths. Photocathodes as electron multipliers have flight heritage, however, sensitivity to contamination is one area of study for this application. Stable metals such as gold, tungsten, aluminum and platinum are all good candidates for the photocathode material.

Development of a centrally-obscured Fresnel zone plate (FZP) to improve the performance of the GOES EUVS

James C. Bremer
Swales Aerospace

To improve the performance of the GOES EUVS channels, a new approach using Fresnel zone plates (FZP) is proposed. A free-standing FZP, like a transmission grating, is composed of alternating open and opaque zones. FZP's have zones configured as concentric circular rings. Whereas in contrast, gratings have linear zones at constant spacing. The radius of each ring is approximately proportional to the square root of the zone number. The FZP focuses radiation of a single wavelength by diffraction, blocking out zones of negative interference from the wave front converging to the focal point. As a result of this focusing feature of FZPs, the GOES EUVS can use a larger aperture and smaller detector in the GOES channel C and D regions. For the 45 nm wavelength region, and a 10 nm bandwidth, a FZP system is calculated to produce a signal current of 3.5 pA as compared to 0.25 pA from the transmission grating approach currently used for GOES EUVS. The disadvantages are that a dedicated aperture is required for each channel, thus increasing the size of the instrument. Additionally, the fabrication of FZPs and the resultant performance is not at the maturity level of transmission gratings.

Appendix B

Appendix B is the supplemental set of data files in .pdf format, containing the complete presentation of all speakers during the GOES R+ EUV Sensor Workshop held October 28-29, 2002.

File: GOESR_EUV.pdf
Solar EUV Irradiance Variability
J. L. Lean, J. T. Mariska, H. P. Warren
Naval Research Laboratory, Washington DC.

File: SolomonEUV.pdf
File: Stan_backup.pdf
Solar EUV Energy Deposition in the Atmosphere
Stan Solomon and Liying Qian
High Altitude Observatory, National Center for Atmospheric Research

File: solar EUVMarcos.pdf
AIR FORCE SATELLITE DRAG REQUIREMENTS
Frank A. Marcos
Space Vehicles Directorate, Air Force Research Laboratory
Dr. Joseph Liu
Air Force Space Command, Space Analysis Center

File: GOES-R Tobiska.pdf
Improvements in Operational Satellite Drag Estimation
W. Kent Tobiska, Bruce Bowman, Mark Storz, Steve Casali

File: EUV_Conference.pdf
IONOSPHERIC EFFECTS ON SYSTEMS
John M. Goodman
Radio Propagation Services, Inc.

File: NOAA_mcmullin2.pdf
Absolute solar EUV irradiance from SOHO CELIAS/SEM
Donald R. McMullin and Darrell L. Judge
USC Space Sciences Center

File: Woods_NOAA_2002.pdf
Overview of Recent Solar EUV Instruments Overview of Recent Solar EUV Instruments from LASP / University of Colorado
Tom Woods
LASP, University of Colorado

File: GOES N-Q Overview.pdf
GOES EUV Sensor Overview
Rodney Viereck
NOAA Space Environment Center

File: Eparvier_EVE.pdf
SDO EVE: An Example of Future Solar EUV Spectral Irradiance Monitors
Frank Eparvier and Tom Woods
University of Colorado, LASP

File: EUV Filter Technology Final.pdf
Developments in EUV Filter Technology
Rich Capps
Luxel Corporation

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Developments in Si EUV Detectors
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III-V Compound Semiconductors for UV detectors
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File: Solar Blind.pdf
Solar-Blind GOES EUVS Sensors
John Seely
Space Science Division, Naval Research Laboratory

File: EUV_FZP.pdf
Development of a centrally-obscured Fresnel zone plate (FZP) to improve the performance of the GOES EUVS
James C. Bremer
Swales Aerospace

Appendix C

Attendance List
Satellite Requirements Workshop
NOAA Space Environment Center
Boulder, CO
October 28-31, 2002

Appendix C is the supplemental file, Appendix_C_attendance.pdf